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THE INTELLIGENT TECHNOLOGY OF SMART FISHING USING A HETEROGENEOUS ENSEMBLE OF UNMANNED VEHICLES

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ІНТЕЛЕКТУАЛЬНА ТЕХНОЛОГІЯ СМАРТ-РИБАЛЬСТВА ЗА ДОПОМОГОЮ ГЕТЕРОГЕННОГО АНСАМБЛЮ БЕЗПІЛОТНИХ АПАРАТІВ

The paper addresses the use of heterogeneous ensembles of intelligent unmanned vehicles in such a perspective field of innovations as an unmanned fishery. The issues of joint activity of unmanned vehicles of different types in fishing operations based on intelligent technologies are investigated. The “smart fishing” approach based on the joint fishing operation model is proposed. The operational framework that includes missions, roles, and activity scenarios embedded in the discretized spatial model is presented. The scenario activities are considered as the sequences of pentad that determine executing specific functions concerning the specified waypoint, timepoints, and the states of vehicles. The definition of the plan as the scenario prototype that needs adjusting to the conditions of the situational context is proposed. The coordination problem regarding the joint activities of the unmanned vehicles and their scenarios is defined and the coordination framework based on the distributed common board model and coordination primitives is presented. The prototype of the intelligent scenario-based system including the implementation of both operational and coordination frameworks developed for the control of unmanned vehicles is described. This system makes unmanned vehicles capable to absorb all the latest advances in intelligent technologies to perform smart fishing operations jointly in a large heterogeneous group. The proposed approach to smart fishing using intelligent technologies makes it possible to detach fishermen from the fishing activities dangerous to their life and health, to reduce significantly poaching and illegal fishing, to increase the overall efficiency of fishing operations, and even to save the marine ecosystem.

Keywords: smart fishing operation, unmanned vehicle, mission, role, scenario, coordination, synchronization

У статті розглянуто питання використання різнорідних ансамблів інтелектуальних безпілотних апаратів у такій перспективній галузі інновацій як безпілотне рибальство. Досліджено різні аспекти спільної діяльності безпілотних апаратів різних типів у рибальських операціях на основі інтелектуальних технологій. Запропоновано підхід до «розумного рибальства», заснований на моделі спільної рибальської операції, представлено операційний фреймворк, який включає місії, ролі та сценарії діяльності, вбудовані в дискретизовану просторову модель. Діяльність за сценарієм розглядається як послідовність пентад, які визначають виконання конкретних функцій у контексті зазначених точок шляху, часових точок та стану безпілотних апаратів. Запропоновано визначення плану як прототипу сценарію, який потребує пристосування до умов, визначених контекстом ситуації. Визначено проблему координації спільної активності безпілотних апаратів та їх сценаріїв, а також представлено координаційний фреймворк, заснований на розподіленій моделі спільної дошки та примітивах координації. Описано прототип інтелектуальної системи, що базується на сценарії, який включає реалізацію операційного та координаційного фреймворків та розроблений для управління безпілотними апаратами. Ця система робить безпілотні апарати здатними увібрати в себе всі новітні досягнення інтелектуальних технологій для спільного здійснення «розумних» риболовецьких операцій у великих неоднорідних групах. Запропонований підхід до «розумного рибальства» з використанням інтелектуальних технологій дає можливість відсторонити рибалок від небезпечних для їхнього життя та здоров'я операцій риболовлі, значно зменшити браконьєрство та незаконну риболовлю, підвищити загальну ефективність рибальських операцій і навіть якнайкраще зберегти морську екосистему.

Ключові слова: операція «розумного рибальства», безпілотний апарат, місія, роль, сценарій, координація, синхронізація

Introduction

Fish is an important food for all mankind. Thus, the fishery is one of the most important food industries. Due to its growing demand, the fishing fleet increases from year to year, and the total fish catch has also grown. Today, we observe a global trend toward increasing fish consumption. However, the growth of industrial fish catches and their processing is limited both by the recent decrease in fish livestock and several climatic, environmental, and technological factors. Therefore, last year's fishing volumes are large enough but variable. An increase in the volume of fish catches does not depend further on the number of fish fleets or the intensity of its use. Now the volume of the fish catch is regulated by quotas due to the requirements of saving the fish population. Accordingly, the efficiency of the fishing industry that has been traditionally estimated by the catch per fisherman is dropped in recent years, and this is essentially the result of the lack of development in fishing gear and technologies [1]. It is clear that the fishing industry needs modern fishing gear and technologies. Unfortunately, this industry has a relatively low level of innovation due to objective reasons. Most of the modern sophisticated technologies are not mentioned in maritime international codes and conventions (i.e., SOLAS, UNCLOS, COLREGS, STCW, ISM, IMO, etc.) and this hinders the use of unmanned vehicles equipped with onboard sensors and gears, which can significantly improve the efficiency of the fishery. Besides, the active use of unmanned technology will allow a significant number of fishermen to remain healthy and even to save their lives since their work is a source of increased danger. Nevertheless, the systematic renovation of maritime international codes and conventions is been conducted, and one can hope that the opportunities for innovation in the fishery will significantly increase soon.

Problem statement

The future of fisheries does not depend on any individual technological innovation, but modern technologies must complement and communicate with each other to help in effective fishing. There are plenty of recent fields of innovations, the results of research and development in which can be exploited in fishery, such as Artificial intelligence, Machine learning, Machine vision, Remote Sensing, Big data analysis and data processing, Unmanned vehicles, etc.

Modern fishing operations are based, first of all, on the search for fish schools. Next, it is necessary to identify fish species and sizes of fish found in the fish school, because a school with main juveniles should not be caught, it should remain in the ecosystem for the fish reproduction. Non-commercial fish varieties should also not be thoughtlessly caught. If a school of fish is determined to be suitable for fishing, then the fishing boat must be navigationally focused on the effective use of special fishing gear to optimal catching of fish. Of course, this is actually a very simplified scheme of the operation, but it is clear that unmanned vehicles (UVs) can be the most appropriate means to accomplish such an operation.

It seems that the use of the unmanned vehicle in an individual manner cannot play a decisive role in providing a technologically innovative and efficient fishing operation. Thanks to continuous improvement, UVs have become much more autonomous and intelligent than just a decade ago. It is also important that they have become much cheaper, which ensures the mass use of UVs in large groups.

Therefore, the problem addressed in this paper relates to the use of large groups of modern intelligent UVs capable of absorbing all the latest advances in the above-mentioned fields of innovations. We will investigate the issues of joint use of UVs of different types in innovative unmanned fishery operations.

Related works

Unfortunately, there is very little literature on the use of UVs in fishing. Most researchers have investigated fishing issues that are loosely related to this topic. For example, there are many works devoted to managing the sustainability of fishery resources [2, 3] or smart fish farming [4]. Nonetheless, there are good reviews on innovative technologies in industrial fisheries [5, 6], but their consideration is restricted to the use of UVs for monitoring

and patrolling fishing areas, so they weakly address the topic. Several works have also been devoted to the investigation of intelligent tools and technologies for monitoring, control, and surveillance of unwanted catches [7, 8] as well as surveillance task for searching and counting fish in fisheries' video [9, 10]. There are also a few papers that address the development of smart fishing gears based on traditional fishing gears such as trails, seines, nets to catch fish as well as acoustic sonar and echo sounders to detect fish [11-13]. Furthermore, there are also exotic attempts to fish directly from aerial UVs [14], but this is more of a sports and recreational activity, rather than industrial fishing.

The automated fishing system has been proposed in [15] that offers an effective method for harvesting the coastal pelagic fish resource. Indeed, it would be the first unmanned fishing system, but it did not use UVs because it has been coastal. Some interesting ideas of using underwater UVs equipped with side sonar, multibeam sonar, and environmental sensors (oxygen, temperature, salinity, turbidity, camera) for fishing and fish farming have been proposed in [16]. This paper listed requirements for onboard sensors and emerging communication (navigation) problems for underwater UVs. However, it considers only a task of trawl net following related to the fishing operations.

The ultimate smart boat vision has been proposed in [17] based on rapid change in such technology as networks, sensors, and artificial intelligence.

New ideas related to the implementation of innovative intellectual methods in fishing operations lead to interesting projects such as SmartFish [18], which is aimed mainly at improving catch efficiency, catch composition and catch quality in pelagic and demersal fisheries, reduction in fishing mortality, the capture of protected species, and the environmental impact of fisheries. Within this project, plenty of smart technologies have been proposed dedicated to pre-catch size and species recognition based on optical and hydroacoustic technologies (SeinePrecog), real-time detection of organisms that are undetectable using conventional fish finding techniques (i.e., echo sounders and sonars) (FishFinder), providing detailed information on species and sizes entering the trawl (TrawlMonitor), using LED technology to optimize the catching performance of trawl fishing gear (SmartGear), as well as a hardware and software infrastructure for acquisition, analysis, and presentation of data from onboard catch monitoring systems (FishData).

It is known that UVs and sensors are becoming smaller, cheaper, and more powerful, so it is now realistic to combine all modern technologies centered around UVs. Since UVs find more and more applications and cover more and more fields in the sea and ocean environment, it's time to consider their application in such a field as smart fishing.

The aims of the paper

Considering the above-mentioned reasons, the most topical issue for today is an investigation of intelligent technologies in the context of smart fishing operations. We suppose that smart fishing operation is performed by a large group of UV. Such a group can include underwater, surface, and aerial UVs simultaneously, so it can be heterogeneous. Since each of the UV plays its role within the group, performing a certain individual mission during a common joint fishing operation, such structure of a group of UVs is called an ensemble, which distinguishes from other currently known structures of UV groups (i.e. swarms, flocks, etc.) [19]. Thus, the paper aims to propose an approach to smart fishing using the heterogeneous ensemble of UVs with proper coordination.

Methodology

Let us imagine an intelligent fishing operation (smart fishing) performed jointly by a wide range of UVs of various types and classes involved in the implementation of certain missions based on their competence. For example, unmanned aerial vehicles can be involved either individually or in small groups in the search for schools of fish. Unmanned underwater vehicles, either individually or in groups, can effectively use sensors to identify species of fish and their numbers in schools, assessing the feasibility of catching them. Un-

manned underwater vehicles have other group tasks such as driving fish schools to fishing gear, trawl net following in order to estimate the volume of the catch and the occupancy of the trawl net. Unmanned surface vehicles (i.e., unmanned boats) can carry fishing gear, so they also can be used individually, in pairs, or small groups depending on the kind of gear. Naturally, we need to use a relatively large vessel in the fishing operation as a carrier of all the above-mentioned UVs that allows them to port (take off or land), recharge, unload the catch, etc. Such a vessel can accumulate and process the caught fish, and of cause, it can be serviced by a team or can also be unmanned soon.

Obviously, the overall goal of such fishing operation will be to catch selectively a given volume of fish of certain species and sizes, with a minimum expense of time, fuel, oil, etc., and, of course, with a minimum negative impact on the ocean environment. In this context, UVs jointly, sequentially, and synchronously perform assigned individual or group missions until the overall goal of the operation is achieved. The assignment of missions to unmanned aerial vehicles is associated with their functional and technical capabilities, which determines their ability to perform certain roles. UVs can be universal, allowing them to perform several different roles, or specialized, adapted to a specific role. Thus, let us define the joint fishing operation model and the heterogeneous ensemble of UVs concerning its composition and structure.

The joint operation models

Suppose U is a set of UVs, F is a set of their parameters, Φ is a set of their functions, and Cl is a set of classes of UV. Each UV $u_i \in U$ belongs to a certain class $cl_k \in Cl$ according to its parameters and capabilities and can perform a certain set of functions $\Phi_i = \{\varphi_{0k}, \varphi_{1k}, ...\varphi_{mk}\}$. This means that u_i can perform at least one function $\varphi_{lk} \in \Phi$ depending on its class.

Let T be a timescale constructed over an open ordered set of time points $[t_0, ...t_y)$. Suppose G is a set of groups of UV. Each group $g_q \in G$, in turn, is a dynamic set of UVs, since at different time points $t \in T$ such a group can consist of different numbers of different UVs. The state of each UV $u_i \in U$ can be described by a dynamic set of parameters' values (i.e., speed, direction, coordinates, etc.) $F_i(t) = \{f_{i1}(t), ...f_{is}(t)\}$.

Let Ξ be a three-dimensional Euclidean space discretized by a metric grid D of coordinate lines with size δ, certain metric ξ_Ξ, and linear mapping f such that coordinate lines constitute a set of cells having the size $\delta \times \delta \times \delta$, $f : \Xi \to D$. As the result, we obtain the grid $D = \{d_{xyz}\}$ of isometric cubic cells d_{xyz}, where x, y, z meet the cell coordinates. In this way, each cell $d_{xyz} \in D$ is a spatial object of the smallest size. Therefore, the discrete location of each UV, obstacle, or goal is geo-referenced to the certain cell(s) within space Ξ. Cell size δ can usually be determined by the technical capabilities of UVs' sensors and the computing capabilities of their onboard computers.

Suppose each UV $u_i \in U$ can perform a motion function $\varphi_0 \in \Phi$ moving inside space Ξ, changing its state $F_i(t)$ over time, and avoiding both obstacles and collisions with other vehicles. It is clear that UV $u_i \in U$ can also perform any other function $\varphi_j \in \Phi$ depending on its class.

Let $Pos(u_i)$ be a position of UV $u_i \in U$ within a discretized three-dimensional space D, so $\langle Pos(u_i), t_l \rangle = (d_{xyz})$, $d_{xyz} \in D$. Let TP be at certain points in time, WP be a certain waypoint, and FP be a certain state of the vehicle. Clearly, the route of each vehicle can be represented as a certain sequence of waypoints WP with respect to the corresponding TP. In other words, the route can be defined as an ordered array of pairs (TP, WP) as a convenient way to control and coordinate the joint activity of the vehicles, primarily their joint motion.

Assume that any WP can also be represented with a certain approximation as a cell

$d_{xyz} \in D$. Thus, $\langle t_l, Pos(u_i)\rangle = \langle TP, WP\rangle_{(i,l)}$, and a trajectory of UV u_i during the time interval $t \in [t_l, t_m]$ can be determined as a sequence $\left[\langle TP, WP\rangle_{(i,l)} \ldots \langle TP, WP\rangle_{(i,m)}\right]$.

Suppose that UV $u_i \in U$ must take a certain position $Pos(u_i)$ at the time point $t_l \in T$ to perform a specific function $\varphi_j \in \Phi$ (it will be convenient to distinguish functions that can be performed only once in a particular WP (e.g., unload the catch) from functions that can be performed continuously during the motion of the vehicle from one WP to another (e.g., trailing).

Accordingly, a tuple (pentad)

$$\langle t_l, Pos(u_i), F_i(t_l), \varphi_j, t_j\rangle \tag{1}$$

determines that UV $u_i \in U$ has to perform a specific function $\varphi_j \in \Phi$ over time point $t_j \in T$ previously taken the position $Pos(u_i)$ (WP) and having the state $F_i(t_l)$ (FP) at the time point $t_l \in T$ (TP).

Clearly, a sequence

$$Tr(u_i)_l^m = \begin{bmatrix} \langle t_l, Pos(u_i), F(u_i, t_l), \varphi_j, t_j\rangle \ldots \\ \langle t_m, Pos(u_i), F(u_i, t_m), \varphi_k, t_k\rangle \end{bmatrix}$$

is called the trajectory of the vehicle's u_i activity at a time interval $t \in [t_l, t_m]$ that determines completely the activity of the specified UV at a given time interval. It can also be represented as a vector

$$Tr(u_i)_l^m = \begin{bmatrix} \left\langle \langle WP, TP, FP\rangle_{(i,l)}, \varphi_j, t_j \right\rangle \ldots \\ \left\langle \langle WP, TP, FP\rangle_{(i,m)}, \varphi_k, t_k \right\rangle \end{bmatrix}.$$

Consider a multitude of groups $g_1, \ldots g_m \in G$ and separate UVs $u_1, \ldots u_n \in U$ dispersed over the space Ξ perform there a certain joint operation Op aimed at catching fish from found schools. Let H be a set of fish schools. Thus, the position of each founded fish school $h_p \in H$ over time can also be represented approximately within the certain cell $d_{xyz} \in D$ by the pair $\langle t_l, Pos(h_p)\rangle$.

Suppose long-term operation Op consists of a set of missions $M = \{m_1, \ldots m_n\}$, which can be performed either sequentially or in parallel. Each mission $m_j \in M$ can be assigned to a certain UV $u_i \in U$ or a certain small group $g_q \in G$. Let R be a set of roles. The mission $m_j \in M$ can assume one or more specific role(s) that should be assigned to several UVs performing them jointly. Thus, the set of assigned roles R must cover the entire set of missions $M = \{m_1, \ldots m_n\}$ required to operate Op.

Consider the UVs $U_{op} = \{u_i, \ldots u_n\} \subseteq U$ of corresponding classes $\{cl_k, \ldots cl_z\} \in Cl$ united in some groups $G_{op} = \{g_1, \ldots g_m\} \subseteq G$. If UVs $\{u_i, \ldots u_n\} \in U_{op}$ perform certain missions $M_{op} = \{m_1, \ldots m_u\} \subseteq M$ with assigned roles $R_{op} = \{r_1, \ldots r_n\} \in R$ in the context of a certain operation Op, we assume that UVs $\{u_i, \ldots u_n\} \in U_{op}$ constitute a heterogeneous ensemble En defined by the sets of participating vehicles U_{op} and groups G_{op} as well as the sets of operational missions M_{op} and roles R_{op}. Clearly, the ensemble En must have a tree-like structure $Str(En)$ and shape $Shp(En)$; the last determines its dynamic spatial configuration $V(En, t)$. The structure $Str(En)$ represents a structural aspect, whereas the shape $Shp(En)$ represents a geometric aspect of the ensemble concerning the performing operation Op. Thus, $En = \langle Op, U_{op}, G_{op}, M_{op}, R_{op}, Str(En), Shp(En)\rangle$.

If the certain UV $u_k \in U_{op}$ is a member of the En, it must perform a certain sequence of assigned missions $M_k = [m_{k1}, \ldots m_{kn}]$ according to the roles $R_k = [r_{k1}, \ldots r_{kn}]$.

Each role $r_{kj} \in R$ within the mission $m_{ki} \in M$ can be implemented through the execution of a certain activity scenario Ω_{kl}. Usually, the scenario requires that UV must move according to a certain sequence of positions $[WP_{k1}, \ldots WP_{kp}]$ and perform the specified actions in the given WPs/TPs. In this case,

the trajectory of the activity $Tr(u_k)$ is the objectification of the scenario Ω_{kl} during its execution time.

Thus, the scenario of the certain UV mission can be represented as the desired trajectory of its activity determined by a sequence of waypoints associated with the corresponding time points, states (represented as a set of parameters such that speed, direction, etc.), and actions (related to the performing of the specific function(s)).

According to the scenario, UV $u_k \in U_{op}$ at each defined TP must be located at the corresponding cell within space Ξ (WP) having specified state (FP) (optionally) and performing the specific function $\varphi_{hk} \in \Phi$ or the set of functions $\{\varphi_{hk},...\varphi_{sk}\} \in \Phi$.

Let us denote the certain pentad (1) by ρ_{kl} such that $\langle t_l, Pos(u_k), F_k(t_l), \varphi_j, t_j \rangle$. The scenario Ω_{kj} can be represented as a sequence of pentads $\Omega_{kj} = [\rho_{ki},...\rho_{kl}]$, where $t_i < t_l$.

The operational framework

Consider now the operation as a whole. The scheme of the fishing operation $Sch(Op) = \{m_1,...m_n\}$ contains a set of missions that should be assigned for the certain UVs $\{u_1,...u_k\} \in U_{op}$, which are the members of the ensemble En concerning the operation Op. Some of the missions can be performed in parallel but others in sequence, after completing another mission. In its turn, each mission $m_j \in M_{op}$ contains a set of roles $\{r_{j1},...r_{jm}\} \in m_j$. A certain UV can be involved in the implementation of the specific role based on the relevance of its functional and technical capabilities. In its turn, each i-th role r_{ji} within a certain mission m_j can be represented as a multiplicity of alternative activity scenarios $r_{ji} = \langle \Omega_{ji1} | ... | \Omega_{jil} \rangle$. Such a tree-like scheme of the operation is named an operational framework (Fig.1).

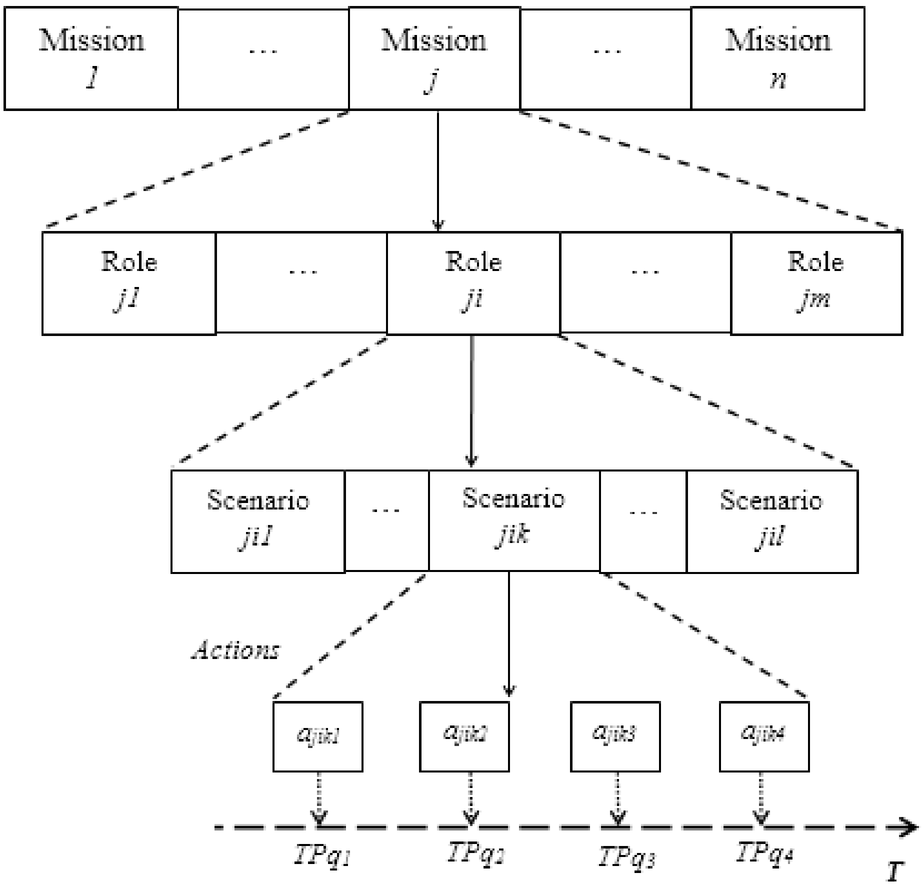

Fig. 1. The operational framework structures

It can be also represented as

$$Sch(Op)=\begin{Bmatrix}\{\langle\Omega_{111}|...|\Omega_{1ml}\rangle,...\langle\Omega_{jm1}|...|\Omega_{jml}\rangle\},...\\ \{\langle\Omega_{n11}|...|\Omega_{nml}\rangle,...\langle\Omega_{nm1}|...|\Omega_{nml}\rangle\}\end{Bmatrix}$$

where the first index of each scenario represents the mission within the operation Op, the second index represents the role within this mission, and the third index represents the alternative of the scenario within this role.

The multitude of all scenarios executed jointly and simultaneously within the operational framework distributes the activity of the ensemble En in space and time. Thus, the reciprocal location of WPs of all involved UVs $\{u_i,...u_n\}\in U_{op}$ at the certain TPs that correspond to the specific time point $t_j\in T$ determines the spatial configuration $V(En,t_j)$ of the ensemble En.

The structure $Str(En)$ of the ensemble En depends on the operational framework $Sch(Op)$ while the latter depends on the change of spatial positions of all members of the ensemble En and their roles $r_{kj}\in R_{op}$ as well as on the change of locations of the founded schools of fish $Pos(h_j,t_l)$, $h_j\in H$, $t_l\in T$. Further, the spatial positions of all members of the ensemble En constitute its scheme $Shp(En)$. This scheme depends significantly on the current situation Sit, which, in turn, is determined by a combination of the spatial distribution of the founded schools of fish, the spatial configuretion $V(En,t)$ of the ensemble, states of UVs, state of the environment, given constraints, etc.

Let us define a procedure $\varsigma_U(U_{op},r_{kj})\to u_k$ that assigns the given role $r_{kj}\in R_{op}$ to the most appropriate UV $u_k\in U_{op}$ based on the relevance of its functional and technical capabilities and a procedure $\varsigma_S(r_{kj},u_k)\to\Omega_{kj}$ that choose the appropriate scenario Ω_{kj} based on the given role $r_{kj}\in R_{op}$ and its performer $u_k\in U_{op}$.

Suppose each UV $u_k\in En$ has a relevant pre-built plan $Pl(M_k)$ for performing each feasible mission $m_j\in M_{op}$ represented as a certain prototype of scenarios in the context of the current situation Sit. In this way, the fishing operation Op can be imagined as the implementation of a certain mutual plan $Pl(Op)=Pl(m_i)\circ...\circ Pl(m_l)$ consisting of the plans for individual missions $m_i,...m_l\in M_{op}$ executed by UVs $u_i,...u_l\in U_{op}$ according to their roles $r_j\in R_{op}$ within the ensemble En.

Each prototype $Pl(m_k)$ is the initial plan that can be determined by the appropriate scenario Ω_{kj} indicating the sequence of required positions and functions performed but having only abstract (formal) parameter values. As soon as the actual parameters will be substituted in place of formal parameters corresponding to the current situation Sit, this plan will be implemented to a specific scenario of activity containing the trajectory of activity $Tr(u_k)$. Thus, the initial plan of the entire fishing operation $Pl(Op)$, as well as the relevant mission plans $Pl(m_k)$ of the individual UVs $u_k\in En$, should be defined based on the mutual spatial position of the vehicles (performers) and positions of the detected schools of fish h_j that can be targeted for these missions.

The implementation of the above-mentioned plans can usually be disrupted. Clearly, the change of the positions of any moving objects, i.e. vehicles, obstacles, and fish schools lead to the change of the plans by updating the values of the actual parameters, which in turn leads to reprogramming or even changing scenarios. Furthermore, due to the unpredictability of the environment (weather conditions, unforeseen obstacles, etc.) UVs $u_k\in En$ are exposed to many dynamic and situational disturbances, so their planned trajectories $Tr(u_k)$ can be violated. They also must avoid collisions and obstacles by maneuvering; this also requires the proper correction of the assigned scenario Ω_{kj}. Thus, the plan $Pl(m_k)$

often needs to be changed "on the fly" by replacing, adding, or removing some pentads ρ_{kl} within $Tr(u_k)$.

The planned trajectories of the UVs u_0 and u_1 to perform the mission of the catch school of fish h_1 are shown in Fig. 2, a.

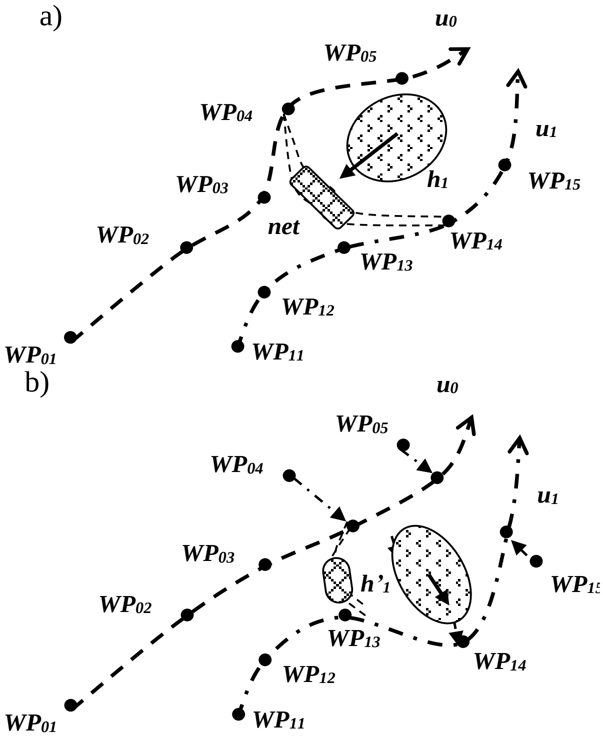

Fig. 2. Changing the scenarios of the UVs under the current situation

The transformation of the trajectories of both UV u_0 and u_1 in response to the situational perturbation caused by the change of the motion direction and speed of the school of fish h_1' is shown in Fig. 2,b. The response to the situation that occurred is obtained through the changes in the waypoints WP_{04}, WP_{05}, WP_{14}, WP_{15} corresponding to the time points TP_4, TP_5.

Clearly, there is always a set of restrictions $L = \{l_1, ... l_w\}$ on the distances, bearings, angles, relative speed, and other parameters imposed on the UVs' joint activity due to the used fishing gear, marine rules, and regulations, etc. (Fig. 3). Therefore, any changes in scenarios or trajectories of the UV should not violate the specified restrictions L.

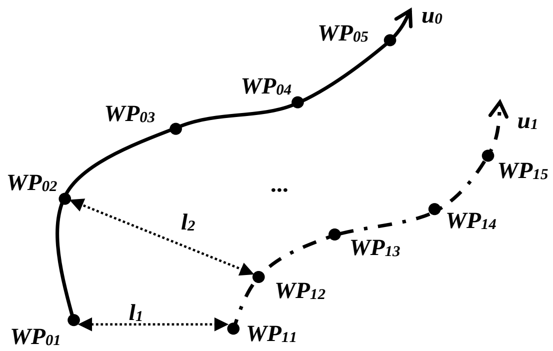

Fig. 3. The trajectories of the vehicles u_0, u_1 with restrictions

Suppose the scenario is a changeable sequence of actions $\Omega_{kj} = \left[a_{kj1}, ... a_{kjq}\right]$, where each action a_{kjl} can be considered as a certain change in the values of UV's activity parameters (e.g., motion speed or direction). Let any change of any parameters of the joint activity of UVs within the ensemble En be considered as events.

Every event that arises within Ξ cause the situation Sit. Since the conditions for the execution of the current scenario Ω_{kj} for the certain UV $u_k \in En$ can be broken, definitely, there is a need to respond to the event in a timely and adequate manner.

Such response to the event can be implemented by changing the mission plan $Pl(m_k)$, rebuilding, adjustment, adaptation of the current scenario Ω_{kj} through addition, replacement, or removal of certain pentads, searching for a new appropriate scenario Ω_{kj}', or even changing the shape $Shp(En)$ or the structure $Str(En)$.

Since the arising event can lead to a change in the conditions of the scenario execution not only for individual UV but for several UVs or even an entire group of UV at once, all of them can begin to simultaneously react to the event by changing their plans and scenarios. Thus, the main challenge of the fishing operation Op is the joint activity of the performers $\{u_i, ... u_n\} \in U_{op}$ embodied in the simultaneous change of their scenarios $\Omega_i, ... \Omega_n$.

Since the changes in the scenario for one of the UVs lead to a change in the conditions for the scenario execution for the other UVs, there is a need to solve the coordination problem for their activity trajectories $Tr(u_1),...Tr(u_n)$ that should be synchronized in time and space.

Coordination problem

Let us define a coordination problem. Consider the set of timepoints $TP \subseteq T$. Suppose $<_T$ is a strict order and ξ_T is a metric imposed over T.

Suppose the set WP is a set of waypoints divided into two disjoint subsets: the subset WP_1 of waypoints that are capable of relocation and the subset WP_2 of waypoints, which can not be relocated. The set WP_2 is always related to either target (final points) for UVs' motion or waypoints, within which UV should perform any function φ_i that differs from φ_0. In the latter case, if UV needs to perform a continuous function φ_i, its activity trajectory must contain both initial and final waypoints that can not be relocated. The other waypoints can be considered as capable of relocation.

An example in Fig. 4 shows the activity trajectories of two vehicles, u_0 and u_1. The waypoints capable of relocation are shaded there while hollowed waypoints can not be relocated. The necessity of relocation of WPs arises in response to the events. Since events caused by certain disturbances appear (or disappear) dynamically, the coordination task arises (or terminates) sequentially.

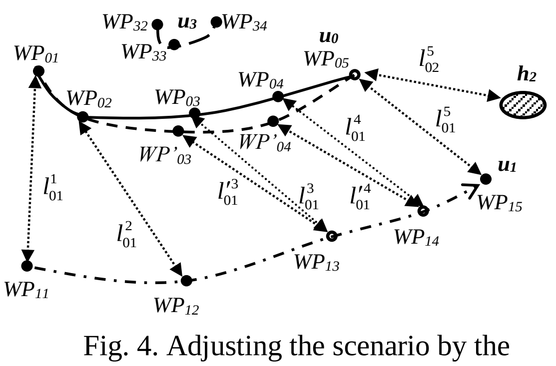

Fig. 4. Adjusting the scenario by the relocation of the waypoints for UV u_0

The coordination task I_{kj} for UV $u_k \in En$ at the given TP t_j can be solved by the procedure that adjusts the executing scenario Ω_{ki} corresponding to the situation Sit at the moment t_j. The solution obtained by this procedure is a time-ordered sequence of actions $\left[(t_j, a_{i1}),(t_{j+1}, a_{i2}),...(t_{j+k}, a_{ik})\right]$ within the scenario Ω_{ki}. Obviously, all WPs within Ω_{ki} corresponding to TPs $t_j, t_{j+1},...t_{j+k}$ will be relocated in the context of the performed actions $a_{i1}, a_{i2},...a_{ik}$. Moreover, WPs related to the scenarios of the other UVs of the ensemble En might also need to be relocated.

To obtain such a solution, we should first build a network using a partial order relation $\prec_I$ imposed over the set of coordination tasks such that $\Im = (\{I_{11}, I_{24},...I_{nm}\}, \prec_I)$. The constraints related to the nodes of this network should be tested on their satisfaction looking through $\Im$ in $\prec_I$-ascending order. If some constraints are violated, the coordination task must be solved for the corresponding pair of vehicles. We assume that each $\Im$ node contains a set of constraints $\{l_{i1},...l_{ik}\} \in L$ imposed on the activity of UV u_i, and a procedure ς_{ik} can be used for checking the constraint l_{ik} satisfaction. Thus, the set of synchronization points (SP) should be determined and adjusted in time and space to solve the coordination task.

The strict order $<_T$ allows us to define for each u_k and u_l such synchronization points t_S that $\exists t_{ki}, t_{lj} \mid t_{ki} = t_S \wedge t_{lj} = t_S$. Since one can look through the scenarios Ω_{ki}, Ω_{lj} in $<_T$-ascending order, all TPs $t_j, t_{j+1},...t_{j+k}$ can be enumerated to use them as synchronization points. The set of the possible WPs $w^* = \{w_{kj1},...w_{kjq}\} \in W_1$ for UV u_k can be obtained based on the cinematic models of UV u_k and the corresponding set of WPs $w_{ij} \in W_1$ obtained based on the cinematic model of UV u_l (Fig. 5). One of them should be chosen to

relocate corresponding WP s within the activity trajectory $Tr(u_k)$ in such a way that the set of imposed restrictions L must not be violated. A good idea is to use the constraint-satisfaction approach considering synchronization points as variables and w^* as its domain we use.

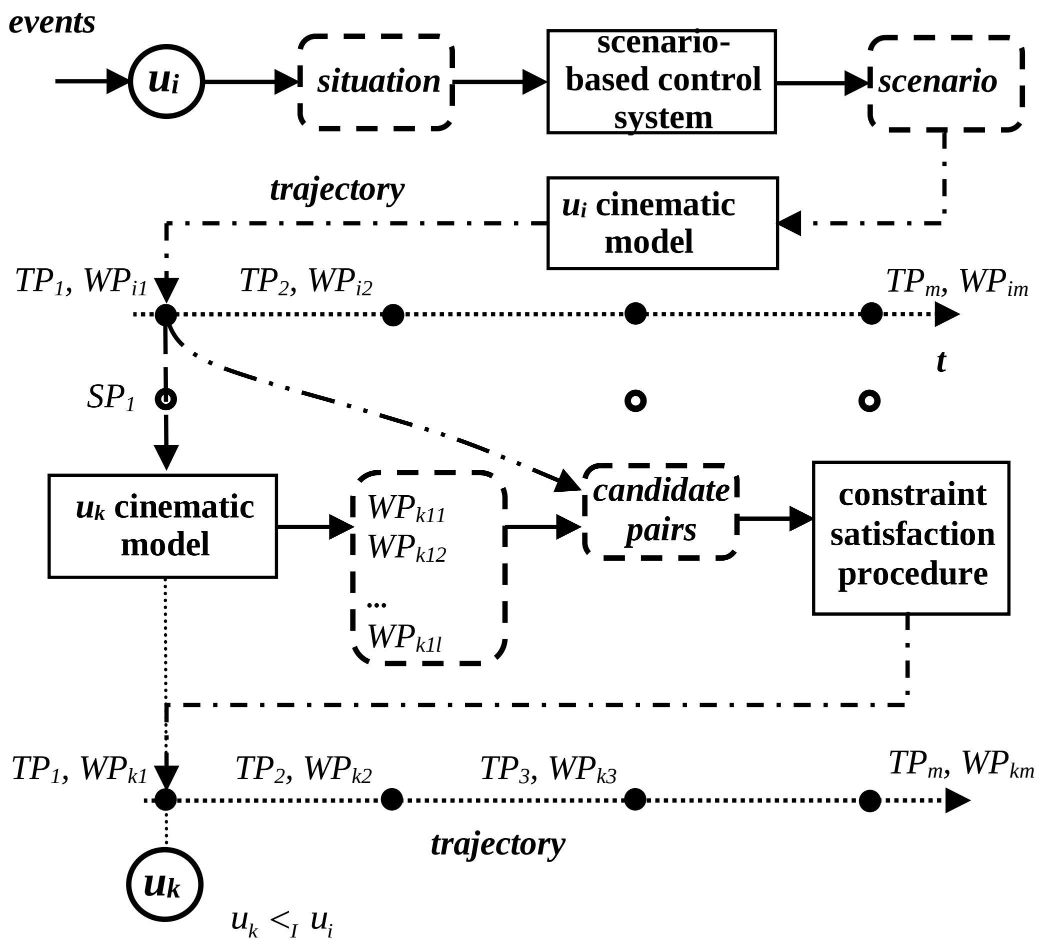

Fig. 5. Process of pairwise vehicles coordination

The solution of the coordination problem $K:\left(\{\Omega_i,...\Omega_m\}\right)\rightarrow\{\Omega'_i,...\Omega'_m\}$ for the entire set of UVs $\{u_i,...u_n\}\in U_{op}$ participated in the ensemble En is to arrange the necessary synchronization points within the correspondding scenarios $\Omega_{ij},...\Omega_{mp}$ using the constraint satisfaction method assuming that SPs are variables and WPs are their domains for each pair of the vehicles $u_i,u_j\in En$, which satisfies the set of given constraints at each TP such that

$$\left\{\begin{matrix}\left(\langle WP,TP\rangle_{(i,l)}...\langle WP,TP\rangle_{(j,l)}\right),... \\ \left(\langle WP,TP\rangle_{(i,m)}...\langle WP,TP\rangle_{(j,m)}\right)\end{matrix}\right\}.$$

Clearly, the accuracy of the solutions of the coordination task essentially depends on the accuracy of the initial information.

The coordination framework

Regardless of the moving environment UVs participating in the fishing operation are equipped with a set of sensors to observe the operational space and monitor the activity of all objects within this space. For example, aerial UVs use high-resolution cameras to provide surveillance and avoid collisions, but underwater UVs use side and multibeam sonars, oxygen and temperature sensors, cameras, etc.

UVs also need navigation to accurate geo-referencing of vehicles, obstacles, and schools of fish. Aerial UVs use GPS receivers

and inertial measurement units for self-localization and navigation while underwater UVs use compasses, doppler logs, ultra-short baselines, etc.

Regardless of the type of sensor, it has limited accuracy, and the number of sensors in UV is also limited for technical reasons. This causes only partial visibility of the environment that leads to inaccuracy, incompleteness, and uncertainty of observations.

However, the overall efficiency of the fishing operation depends on the success of finding relevant activity scenarios for all missions' performers, that definitely depends on the completeness and accuracy of available information to seek appropriate scenarios. In other words, given the limited observations captured by sensors, the coordination of UVs activity relies not only on the synchronization of their activity scenarios provided through adjusting their synchronization points but also on the synchronization of information about the operational space observed by individual UVs within the ensemble. Thus, UVs need to know more about the positions, states, and actions of other UVs within the common operational space, both for safety reasons and for the reasons of successful completion of their missions.

Consider the above-mentioned three-dimensional Euclidean space Ξ and its discretized spatial model D.

Let us define a model of the distributed common space of UVs observations in the form of a common distributed board Ψ. Each item ψ on board Ψ corresponds to a specific cell $d_{xyz} \in D$. Thus, each element denoted by coordinates (x, y, z) is a structure $\psi_{xyz} = \{X_{1xyz}, \ldots X_{nxyz}\}$, which contains the values of the attributes that determine the observed state of the cell d_{xyz} (Fig. 6). These attributes depend on the joint mission of the UVs and the process of their activity. Thus, for smart fishing tasks the common board can include such attributes as x_1 – the species of fish in the school, x_2 – the average weight of fish in the school, x_3 – the current position of the fishing gear (identifier), x_4 – the current position of UV (identifier), x_5 – the presence of an obstacle, etc. Each attribute can be expanded into a set of sub-attributes, for example, x_{41} – the motion speed, x_{42} – the motion direction, etc.

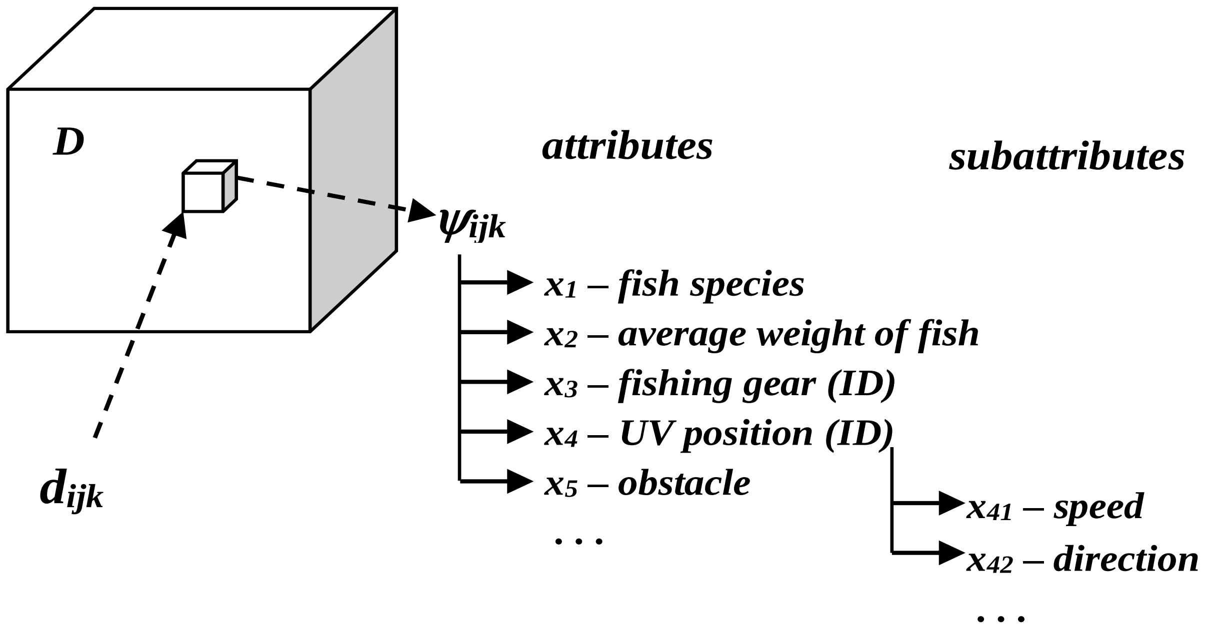

Fig. 6. Distributed common board model

The distributed three-dimensional common board Ψ provides transparency of information and creates a common information environment, which is provided for all UVs that are the members of the ensemble En and located within the space of joint operation Op. Given the inaccuracy of the sensors, each attribute of the cell d_{xyz} can be supplemented by a certain value μ having the range $[0,1]$ to provide the confidence of the corresponding feature within the cell d_{xyz} according to obtained observations. Taking into account that different UVs of the ensemble En can simultaneously observe the operational space Ξ storing the values of attributes and parameters in the same cell, it is expedient that each parameter X_m should be stored as a tuple $X_m = \langle (x_1, \mu_1), ...(x_i, \mu_i), ...(x_n, \mu_n) \rangle$, where x_i is a value of the parameter X_m observed by i-*th* UV and μ_i is the confidence assessment of i-*th* UV concerning the value of the parameter x_i.

Thus, UVs should be able to exchange information about the observed attributes of the cells through the common board Ψ. The main condition for the proper use of such coordination tools as the common board Ψ is the coincidence of the starting point of the spatial models and cell sizes within the control systems of each member of the ensemble. It allows exchanging information, transparently storing it on the common board. The coincidence of these parameters can be achieved by synchronization.

Since a distributed approach is used to coordinate the UVs, the common board Ψ might not be a physical object within operational space Ξ, but a certain virtual entity, so each UV can have its local image of the virtual common board. Thus, UVs must keep a valid copy of the common board and exchange information with other UVs. Coordination primitives (messages) presented in Table 1 are intended for transmission and receiving of the observations (e.g., the spatial positions and expected characteristics of the found schools of fish, the spatial positions and motion parameters of UVs, etc.) through the UV's onboard communication equipment.

Table 1. Coordination primitives

Primitives	*Function*	*Description*
WIT	"Who is there"	UV requests the recall of other UV
WIH d_{ijk}	"Who's here"	UV asks who is in the cell (*i*,*j*,*k*)
IMH d_{ijk}	"I'm here"	UV reports that it's within the cell (*i*,*j*,*k*)
ORG *xyz*	"Starting point here"	UV reports that the starting point has coordinates (*x*,*y*,*z*)
UP	"Get the starting point"	UV requests the coordinates of the starting point
STG d_{ijk}	"Set the pack"	UV establishes the presence of a school of fish in the cell (*i*,*j*,*k*)
OTG d_{ijk}	"Set an obstacle"	UV establishes the presence of an obstacle in the cell (*i*, *j*,*k*)
ATG d_{ijk}	"Assign a destination"	UV sets the target point in the cell (*i*,*j*,*k*)
ISE	"I see"	UV lists all the objects observed by him and their attributes in the space of interaction

Implementation

For each UV $u_k \in En$, the search for a new appropriate scenario Ω'_k under conditions determined by the spatial configuration $V(En, t_j)$ and imposed constraints L is the task of the intelligent scenario-based control system (ISCS).

At the input, such a control system accepts the sequence of events, which determines the current situation (Fig. 7).

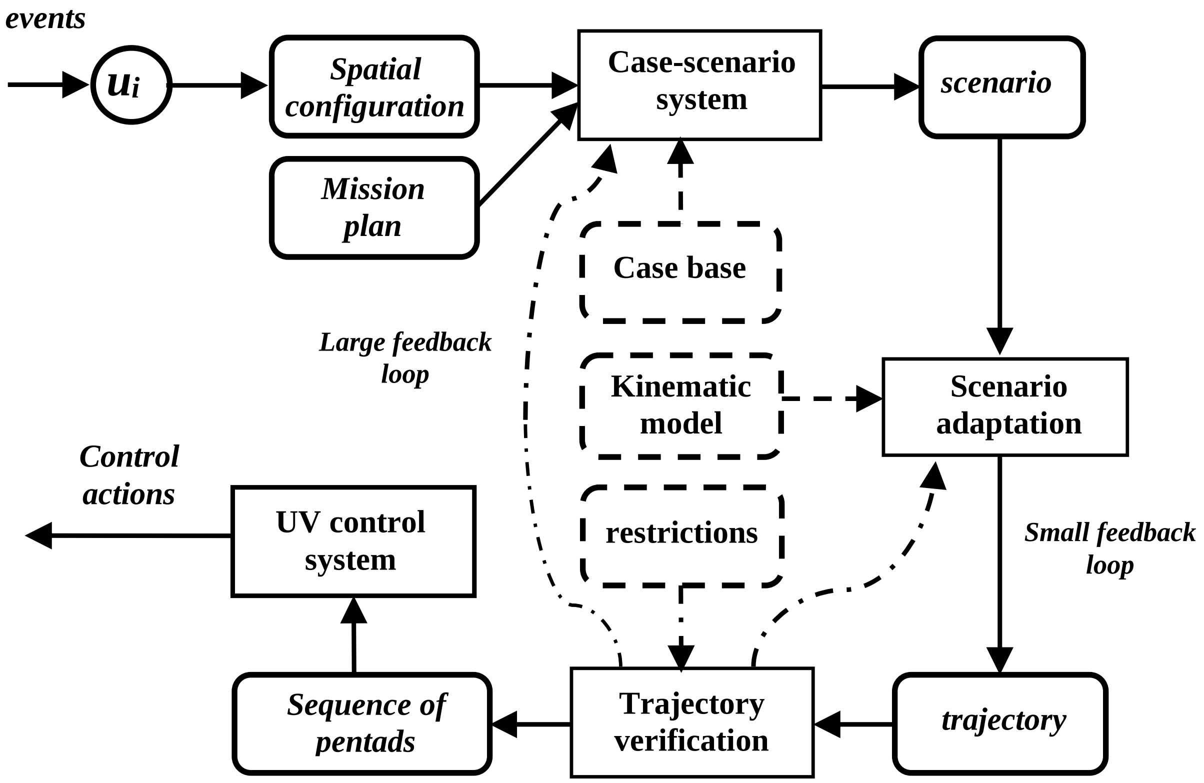

Fig. 7. Information processing within the intelligent scenario-based control system

Based on the mission plan $Pl(m_k)$ and the current spatial configuration $V(t)$, the ISCS of the UV u_k performs the search of the appropriate scenario according to the assigned role r_{kj} with the procedure ς_S. The search result is a scenario Ω_{kj} that must be adapted within a kinematic model. The separate kinematic model-based unit should be used to implement such adaptation resulted in the adjusted activity trajectory $Tr(u_k)$, which must be further verified to test compliance with the specified set of restrictions L. To do such verification, yet another separate unit should be used to solve the constraint satisfaction problem. Thus, if the activity trajectory $Tr(u_k)$ meets all constraints, this trajectory must be converted to a sequence of pentads and transmitted to the low level of the UV control system. Otherwise, if some constraints are violated, the ISCS should try to adapt the scenario Ω_{kj} to the new conditions defined by Sit using a small feedback loop (Fig. 8). Usually, a small feedback loop allows for solving the problem of the scenario adaptation and verification successfully. However, if the problem is not solved within the small feedback in a certain (small) number of steps, a large loop of feedback should be involved that tries to find another scenario Ω'_{kj}, which will be relevant to the current situation Sit.

Thus, the control of the joint activity of a heterogeneous ensemble of unmanned vehicles using ISCS is a complex four-level process.

At the operational level, the main task is to select a suitable operation plan and to build appropriate mission plans based on the current spatial configuration $V(En,t)$. The operation scheme $Sch(Op)$ should be adjusted to the structure $Str(En)$ and shape $Shp(En)$ of the ensemble En. Using the operational framework, the scheme $Sch(Op)$ must be decom-

posed into a set of scenarios Ω_{kj} for all roles $r_j \in R_{op}$ assigned to the UV $u_k \in Str(En)$.

At the mission level, each UV executes chosen scenarios concerning the roles assigned to it. The ISCS converts the scenario to the corresponding sequence of pentads $\langle t_l, Pos(u_k), F(u_k, t_l), \varphi_j, t_j \rangle$ taking into account the set of the given constraints. The ISCS receives observations captured by sensors, transforms them into the event streams, and checks the spatial configuration $V(En,t)$. In the case of the changes detected in the spatial configuretion, if the mission plan is affected by these changes, the search for a new mission plan begins, otherwise, the coordination level procedure is called.

At the coordination level, the sets of waypoints and timepoints of joint vehicle activity should be agreed upon under the selected UV scenarios, then the admissibility of each waypoint/timepoint in the pentads should be evaluated to avoid dangerous areas and lack of schools of fish.

At the low control level, UVs receive a sequence of pentads at the input, generates the appropriate changes of the certain parameters' values $f_{i1}(t),\ldots f_{is}(t) \in F_i(t)$, and transforms them in the sequence of low-level control actions transferred to the UV's actuators.

The prototype of the ISCS including the implementation of both operational and coordination frameworks has been developed based on the onboard microcontroller STM32F429 (Cortex M4 processor 180 MHz, internal RAM 256 KB, and flash memory 2 MB, external memory module QSPI Flash N25Q512). To develop the ISCS, C++ programming language and GNU tools for embedded ARM processors have been used.

Fig. 8 shows the place of the ISCS in the general structure of on-board equipment intended for the control of UVs' joint activity within the heterogeneous ensemble during the fishing operation.

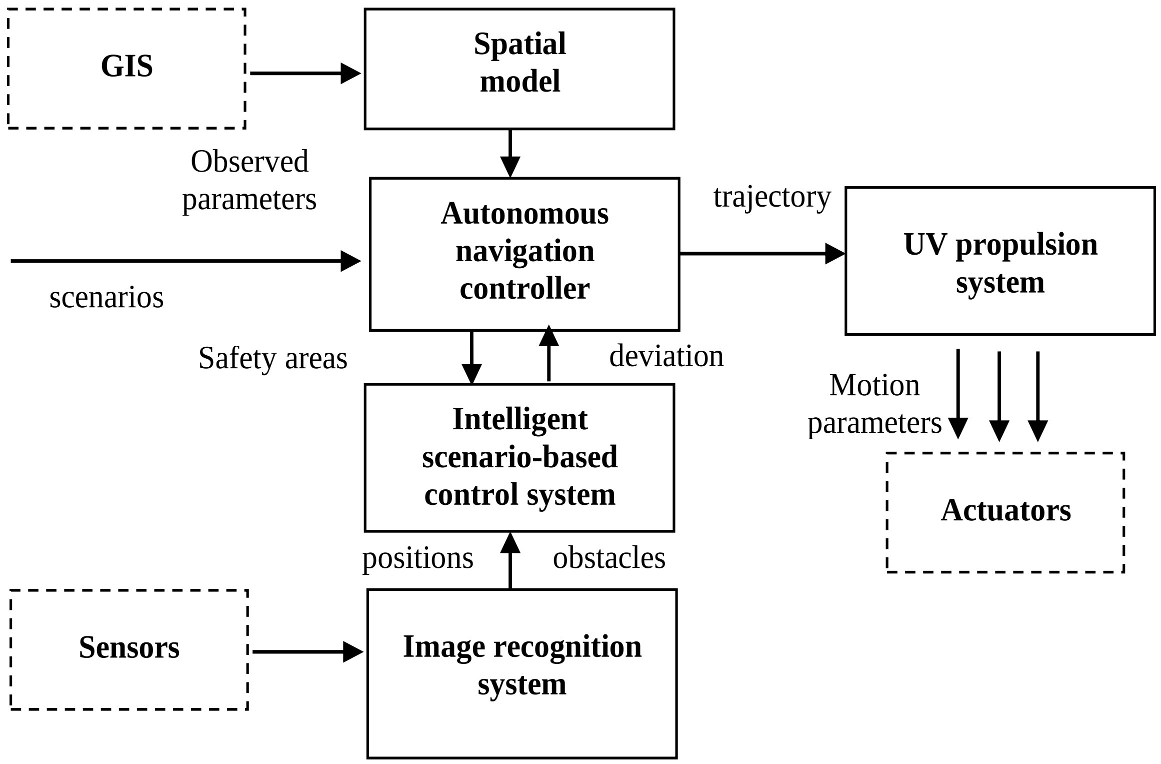

Fig. 8. The general structure of the UV onboard system based on the ISCS

Conclusions

The paper presents the idea of smart fishing operations based on the joint activity of the heterogeneous ensemble of intelligent unmanned vehicles of various types. This idea is embodied in the proposed "smart fishing" operation based on both the model of the joint fishing operation and the model of the heterogeneous ensemble of unmanned vehicles regarding its composition and structure. The operational framework presented in the paper includes missions, roles, plan prototypes, and activity scenarios, which are based on the discretized spatial model. The coordination framework is also presented in the paper to solve the coordination task based on the distributed common board model and coordination primitives. The paper describes a prototype of the intelligent scenario-based system developed for the control of unmanned vehicles including the implementation of both operational and coordination frameworks. It allows the UVs to perform smart fishing operations jointly in a large heterogeneous group.

The proposed approach to smart fishing using intelligent technologies makes it possible to detach fishermen from the fishing activities dangerous to their life and health, to reduce significantly poaching and illegal fishing, to increase the overall efficiency of fishing operations, and even to save the marine ecosystem.

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